Invited Paper

Advances in instrumentation at the W. M. Keck Observatory

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ABSTRACT

In this paper we describe both recently completed instrumentation projects and our current development efforts in terms of their role in the strategic plan, the key science areas they address, and their performance as measured or predicted. Projects reaching completion in 2012 include MOSFIRE, a near IR multi-object spectrograph, a laser guide star adaptive optics facility on the Keck I telescope, and an upgrade to the guide camera for the HIRES instrument on Keck I. Projects in development include a new seeing limited integral field spectrograph for the visible wavelength range called the Keck Cosmic Web Imager (KCWI), an upgrade to the telescope control systems on both Keck telescopes, a near-IR tip/tilt sensor for the Keck I adaptive optics system, and a new grating for the OSIRIS integral field spectrograph.

Keywords: Adaptive Optics, Infrared, Instrumentation, Integral Field, Multi-object, Spectroscopy, Telescope Control, Visible

1. INTRODUCTION

For the past 19 years the W. M. Keck Observatory (WMKO) has played a leading role in U.S. astronomy and astrophysics. The two 10 m Keck telescopes, located at one of the world's premier sites for astronomy, were the first of a new generation of very large ground-based optical/infrared telescopes. The first Keck telescope began science operations in May of 1993, and the second Keck telescope started science operations in October of 1996. The telescopes feature a highly capable suite of advanced instrumentation for both optical and near-infrared wavelengths, including imagers, multi-object spectrographs, high-resolution spectrographs, and integral-field spectrographs. WMKO has developed and operates sophisticated natural and laser guide star (LGS) adaptive optics systems and related instrumentation on both telescopes. The WMKO telescopes, instrumentation, and adaptive optics systems have proven to be a powerful scientific research facility for the U.S. astronomical community and an excellent training ground for students and post-docs. The two Keck telescopes are the most scientifically productive telescopes in the U.S. observing system. For example, in 2011, 292 refereed publications were published based on data from the Keck telescopes, the highest number of papers per telescope among all ground-based O/IR telescopes. Studies of the citation frequency of publications from various observatories show that WMKO has the highest total scientific impact per telescope of all ground-based O/IR observatories[1]. Two essential elements of the Observatory's scientific leadership are the creativity and talent of the astronomers who observe here, and the Observatory's ability to offer astronomers the most advanced instrumentation to use for their observations. To develop new instrumentation it is clearly essential that observatories, like other scientific facilities, keep pace with advances in technology. Technological advancement at WMKO is accomplished through the Observatory's development programs in instrumentation and adaptive optics, and through the upgrading and replacement of critical infrastructure.

2. BACKGROUND

The Observatory was constructed with private funds donated by the W. M. Keck Foundation and is operated in partnership by the California Institute of Technology (CIT), the University of California (UC), and NASA. The Observatory facilities are located on Hawaii Island at summit of Mauna Kea (4,160 m above sea level) and the Observatory's headquarters are located in Waimea, HI. Instrumentation is developed through collaborations between WMKO and academic and commercial organizations. The main centers for the construction of WMKO instrumentation

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are the optical/infrared group at CIT, the Infrared Laboratory at the University of California, Los Angeles (UCLA), and the UCO/Lick Observatory located on the campus of the University of California, Santa Cruz (UCSC).

2.1 The WMKO Observing Community

Access to science observing time with the Keck telescopes is determined by time allocation committees (TACs) representing the institutions with direct interests in the Observatory: CIT and UC each with a 35% share, NASA with a 16.5% share and the University of Hawaii (UH) with a 12.5% share.

The Keck telescopes are available to the entire U.S. astronomy community through NASA's partnership in WMKO and through the National Science Foundation (NSF) funded Telescope System Instrumentation Program (TSIP). WMKO has exchanged observing time with TSIP since semester 2003A, and from semester 2006A through semester 2011B WMKO has made 128 nights available to the National Optical Astronomy Observatory (NOAO). Keck telescope nights have been the most heavily subscribed observing time offered by the NOAO TAC (note the average oversubscription factor of 5.1 for Keck I and II reported in Table 2 of NOAO's ALTAIR Committee Report[2]).

In addition, exchanges with the Gemini Observatory over the last 5 years have totaled 32 nights. The NASA, NOAO, and Gemini time are directly available to the entire U.S. community. In a search of the WMKO observing database from 2008 to 2011, a total of 918 unique names were found with the following institutional breakdown: 615 UC/CIT/Yale, 154 UH, 198 NASA community, 118 NSF/NOAO community, 16 Gemini time exchange, 34 Subaru time exchange, and 24 WMKO staff.

The impact of the Keck telescopes on astronomy education is well illustrated by the 240 PhD theses (now averaging 20/year) produced using Keck data as of early 2012. The list of astronomers who made use of WMKO for their theses includes many of the emerging and mid-career leaders in U.S. astronomy. WMKO is currently providing many graduate students and post-docs direct access to the state-of-the-art instrumentation and adaptive optics capability. WMKO's impact on educating technical people has also been high, with numerous students, post-docs, and young engineers involved in WMKO instrumentation and adaptive optics development and commissioning.

2.2 The WMKO Development Programs

The development activities at the Observatory are based on the collective experience of the Observatory staff and our partner institutions in the design and construction of the telescope and its instrumentation over the past 20 plus years. The Observatory operates a carefully managed program of technology research and development in instrumentation and adaptive optics. The Observatory staff also operates and maintains the telescopes, adaptive optics systems and instrumentation. The Observatory provides staff support for every observing night including full time research astronomers and observing assistants (telescope operators).

The Observatory receives guidance in scientific priorities from its Science Steering Committee (SSC), an advisory group made up of leading astronomers from our partner institutions. In collaboration with the SSC and the broad community of astronomers who depend on the Observatory for much of their observing time we have developed a strategic plan that defines long term goals for continued scientific leadership in astronomy. The WMKO strategic plan articulates four science driven themes that guide technical developments at the Observatory. These are high angular resolution, state of the art instrumentation, highly efficient operations, and flexibility. Through an annual process of review the strategic plan is updated, and potential new projects are considered and mapped to each of the themes. The Observatory then uses this list of candidate projects to guide its annual planning and fund raising activities.

The strategic plan is motivated by important questions in the science of astronomy, and is intended to address a broad range of such questions. It is also based on the belief that while the questions may change, the science of astronomy constantly demands the newest and best observing capabilities. The plan recognizes that the Observatory exists in a competitive environment and it is an important responsibility of the Observatory to ensure that its users always have observing capabilities that allow them to compete effectively with astronomers at other observatories.

The Observatory's instrumentation projects span a range of project scales from major new instrumentation developments, to upgrades of existing instruments, and to many smaller projects aimed at improved performance, adding features to enhance usability, or to address issues uncovered during routine operations. Major development projects and upgrades are managed through the Observatory's development programs in instrumentation and adaptive optics. Smaller projects are managed by the operations and observing support groups at the Observatory.

The development philosophy at the Observatory is based on a consistent set of project phases and standards aimed at creating an environment and supporting infrastructure that maximizes the success of each project. The Observatory provides program level oversight for each development project and statements of work define the roles and activities of each of the project teams. Project management is an essential part of each project team, and large projects are normally required to have a full time project manager. Observatory staff members are also part of the project team, and often participate in the development of the instrument as well as taking responsibility for the interfacing of the instrument with the Keck telescopes. While the Observatory holds full authority over each project we view the collaborative and cooperative side of the relationship as the most important element in ensuring a successful outcome.

Most, if not all projects at WMKO are multi-disciplinary, involving optics, mechanics, electronics and software. The most demanding, large-scale projects involve technological efforts in these disciplines that are either at the state of the art or actually push the state of the art forward. There are two strategies that are fundamental to making these kinds of projects successful, an emphasis on systems engineering and a focused approach to research and development.

While “systems engineering” has become a somewhat fashionable term in our community, it is often paid lip service, but not adequately supported. In our context systems engineering has a clear and fairly narrow definition. Systems engineering emphasizes a <u>total view</u> of the system and the problem and solution spaces and seeks to integrate the various scientific and engineering disciplines required in the project into a unified effort that maximizes the opportunities to explore tradeoffs and achieve synergies. The systems engineering effort uses an iterative process that starts with the high level scientific and user requirements, proposes a design concept and then evaluates the ability of the concept to meet the requirements. The emphasis is a user driven, integrated approach to determining the system architecture that partitions the needed functions across subsystems or components. Where viable alternatives exist for a particular architecture there is an opportunity to make tradeoffs or to explore a trade space.

Another key aspect of WMKO’s approach to systems engineering is that all design team members are expected to practice a systems engineering approach to problem solving. A large project may include an engineer whose specialty is “systems engineering” in the broadest academic sense, but this individual is an evangelist for systems engineering principles and practices throughout the project, not the only team member who performs systems engineering functions.

The focused approach to research and development is a key to achieving several important objectives within the project: well managed and contained levels of risk, well managed and contained cost, and timely completion. By focused research and development we mean that new technologies, either new in the fundamental sense of being first discovered or invented for the project, or the results of research being applied for the first time in the project, are used selectively, where they are clearly necessary to meet the performance requirements for the project. As a consequence, where ever possible we re-use designs and design approaches that have been proven to work on other projects, and we discourage both “not invented here” and “re-inventing the wheel”.

A particular characteristic of the larger scale projects, especially instrumentation, is that the combination of a scientific research driven product and the realities of budget and schedule mean that we deliver a prototype or “one of a kind” system as the product. In order to maximize the success of such efforts we are continuously looking for ways to apply the best practices from industry, particularly high technology manufacturing and rapid prototyping. We also emphasize the adoption of industry consensus standards, as well as the use of appropriate regulatory standards to ensure safe and reliable operation.

Finally, we recognize that every project provides an opportunity for learning, including what went well, and where problems were encountered. We now hold “lessons learned” reviews for every major project and we are working towards maintaining a collection of project performance documentation to help guide the planning of future projects. We are also continually upgrading our standards for project planning and management in order to support our strong goal of “getting there first” in a way that also supports high quality products and recognizes the realities of available financial resources.

3. NEW DEVELOPMENTS IN INSTRUMENTATION

3.1 MOSFIRE

MOSFIRE arrived on Mauna Kea on February 16, 2012 (see Figure 1). Commissioning is essentially complete at this time and on-sky performance meets our expectations. A detailed report is given in the paper in these proceedings by McLean et al.[3]. MOSFIRE was developed for WMKO by UCLA, Caltech, and UCO, with funding from TSIP and a generous donation from Gordon and Betty Moore. MOSFIRE will be available for shared-risk observing in semester 2012B.

Briefly, MOSFIRE provides near-infrared (~0.97 to 2.4 μm) imaging and multi-object spectroscopy over an imaging field of view (FOV) of 6.12' × 6.12' with 0.18" px^{-1} sampling. In spectroscopic mode, MOSFIRE has a resolving power of R ≈3,500 for a 0.7″ slit width, and captures most or all of an atmospheric window in a *single* exposure for any slit placed within a 6.12' × 3' field. The instrument employs a custom diffraction grating used in multiple orders (3, 4, 5, and 6) for dispersion in the K, H, J and Y (a.k.a. Z) bands, respectively. The grating is deployable at two discrete angles located by fixed stops which provide a small position shift for spectra on the detector in order to maximize wavelength coverage for K and H at one position and J and Y at the other position.

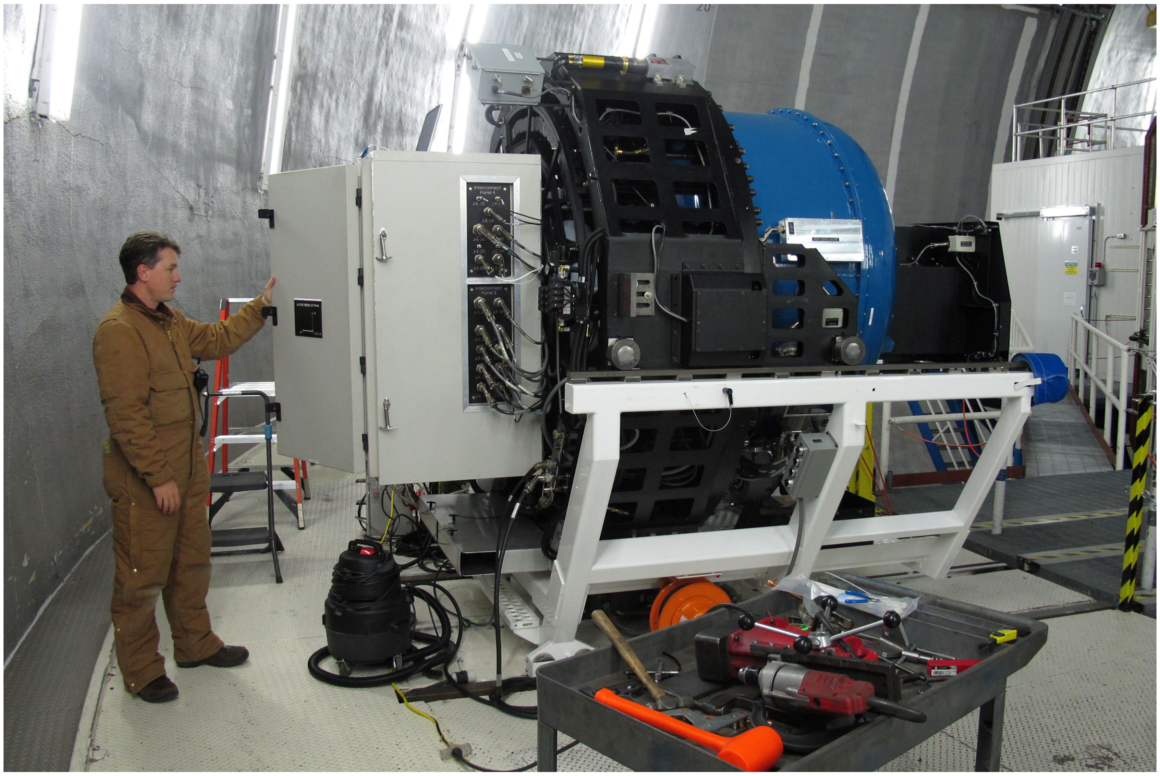

Figure 1: WMKO Support Astronomer Marc Kassis inspects the electronics cabinet at the rear of MOSFIRE shortly after its delivery to the Keck I telescope's Nasmyth deck

Instead of using milled aluminum slit masks requiring daily change-outs as for LRIS and DEIMOS, MOSFIRE features a cryogenic configurable slit unit (CSU) developed in collaboration with the Swiss Center for Electronics and Microtechnology (CSEM) that can position up to 46 slits, each of length 7.0", at a 10 μm (0.014") precision anywhere within the MOSFIRE imaging field of view. MOSFIRE observers can use the slit configuration graphical user interface (GUI) to design mask layouts that can be altered in real time (see Figure 2). Users of slit masks with LRIS and DEIMOS will find the GUI to be very easy to operate, requiring only a list of prioritized potential targets in the same format employed by the AUTOSLIT or DSIMULATOR programs[4] used for mask design on LRIS and DEIMOS. Mask configurations, as well as several other associated data products, are saved to disk.

The height of each individual slit is 7.0", but when two pairs of bars are aligned to produce a longer slit, the light blocking overlap between bars is eliminated and the slit length becomes a contiguous 15". In this way, slits up to 6.1' long can be formed by aligning adjacent slits. Guiding is accomplished via a fixed (6.6' off-axis) CCD camera with a field of view of 2.8' × 2.8', using the same MAGIQ guider system as implemented on other WMKO instruments.

MOSFIRE's software includes a full GUI for the observer, providing an easy means for configuring the instrument (in most cases by a single button click) and taking exposures. Scripts can be written to execute a series of actions. FITS files generated by MOSFIRE contain extensions with detailed information on everything in the instrument, including target names and the physical and sky positions of the masking bars.

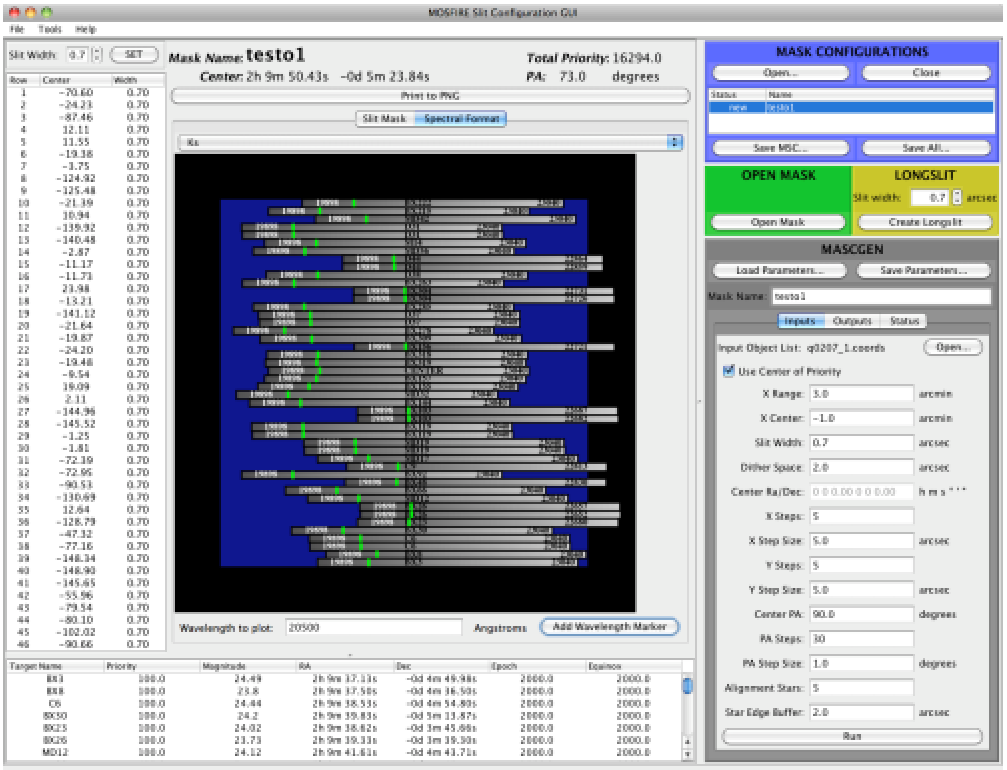

Figure 2: The MOSFIRE Slit Configuration (MSC) GUI allows observers to design slit mask layouts in near-real time and view both the mask layout and the spectral coverage

3.2 Keck I Laser Guide Star Adaptive Optics

WMKO has recently completed the commissioning of a new LGS adaptive optics (AO) facility on the Keck I telescope. Shared risk science observing began in May 2012[5] and full science observations are expected to begin in August 2012. Motivated by the scientific success of the Keck II LGS AO system which has been in full science operations since 2004, WMKO began the development of new 589 nm wavelength guide stars lasers in collaboration with the Gemini Observatory for the Keck I telescope and the Gemini South telescope. The laser[6] was delivered to WMKO in September of 2009, and integration of the laser with the Keck I telescope and AO system took place in 2010 and 2011. Figure 3 shows lasers projecting from both Keck telescopes.

The Keck I laser is installed in a temperature controlled clean room enclosure on the Keck I right Nasmyth platform and the laser light is transported by a free space beam transport system to a 50 cm aperture launch telescope constructed by Galileo Avionica and located behind the Keck I secondary mirror. The on-axis launch location reduces the perspective elongation of the laser spot image resulting in a 37% smaller laser spot, and with more power (21 W vs. 15 W on one night of simultaneous AO observing) the Keck I laser produces a 44% brighter return (R magnitude = 9.9 vs. 10.3). The OSIRIS integral field spectrograph (in operation since 2005 with the Keck II AO system) has been relocated to Keck I and commissioned for science operations with the Keck I AO system.

The results of performance testing indicate that the system offers performance consistent with that of the Keck II AO system. Further discussion of the LGS AO system and the results of on sky testing may be found in the paper by Chin et al. [5] at this conference.

Figure 3: Lasers projecting from both Keck domes (Keck I at right); photo credit: Andrew Cooper

3.3 HIRES Guider Upgrade

We have recently completed the third guider system upgrade using the Observatory's standard MAGIQ guide camera system[7]. This upgrade, to the slit guider of the HIRES instrument, was installed in February 2012 and commissioned in early March 2012. Figure 4 shows an image from the new guider with the FOV of the old guider indicated by the red rectangle.

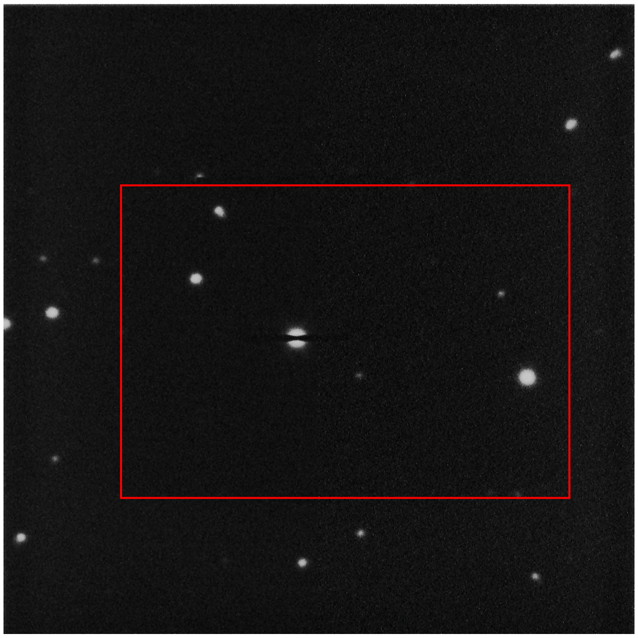

Figure 4: Image taken with the new HIRES slit guider. The FOV of the old slit guider is indicated by the red rectangle.

The old slit guider camera was one of the earliest guide cameras at WMKO, a Photometrics series 200 with a 288 x 384 pixel front illuminated CCD. The new guide camera uses a 1024 x 1024 pixel back illuminated CCD providing finer sampling (0.085"/mm vs. 0.15"/mm) and a larger FOV (1.2' x 1.2' vs. 0.96' x 0.72'). There is a small amount of vignetting at the edges of the guider field due to the limited FOV of the HIRES image de-rotator. The result is an improvement in the guiding performance with HIRES due to a signal to noise ratio improvement of ~2 times combined with the finer sampling of the guider images. The new guider uses the Observatory's standard MAGIQ guiding software and uses the existing HIRES slit guider filter wheels and guider focus mechanism.

3.4 The Keck Cosmic Web Imager

The Keck Cosmic Web Imager (KCWI) is a new integral field spectrograph[8] that is being developed for the Keck II telescope. This spectrograph is an adaptation of the Palomar Cosmic Web Imager (CWI), which has been operating since 2009. CWI[9] was funded by NSF with the primary objective of measuring low surface brightness blue emission from a moderately-sized (40" x 60") field at a spectral resolution of 5,000. By contrast, KCWI is intended as a facility instrument for the Keck II telescope and will add features to the CWI design that allow a wide range of science topics to be efficiently addressed. A sample of these includes measurement of emission from the intergalactic medium (cosmic web), cosmic evolution from z ~2 to 3, black holes at the center of globular clusters, and high-z emission from the era of re-ionization. KCWI is a two channel instrument designed for phased implementation. The instrument with the blue channel (350 to 560 nm) is funded to completion with support from the TSIP program and funding is currently being sought from other sources for construction of the red channel (530 to 1050 nm).

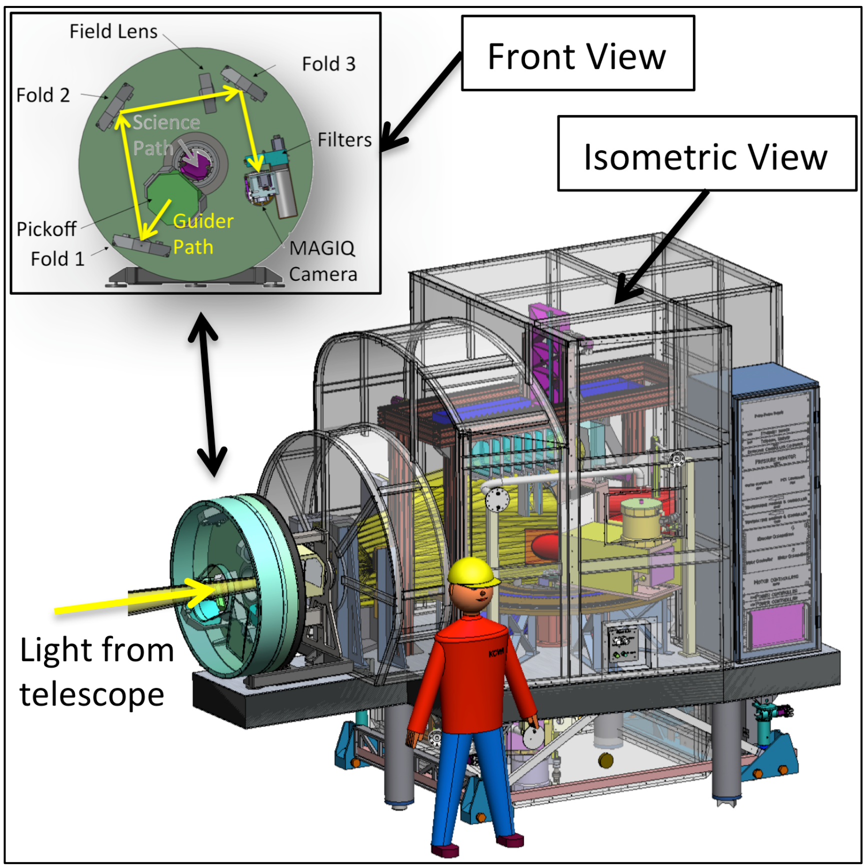

Figure 5: The KCWI instrument shown with transparent enclosure. The inset shows a front view of the tracking guider.

KCWI will operate on the Keck II telescope at the right Nasmyth focal station. The instrument operates in fixed gravity with field rotation compensated by a K-mirror for the science FOV and by a tracking assembly for the instrument's guider. Figure 5 shows a view of the instrument with the outer enclosure transparent. A mannequin is shown as an indication of the overall size. The tracking guider is detailed in the inset; it is located ahead of the science K-mirror and samples a field located 3.24' off axis with a standard 3' FOV MAGIQ guide camera[7]. The tracking guider follows guide stars as they rotate about the optical axis during observations.

A large, custom made optical bench supports all of the instrument's components, and three kinematic mounting points are used to accurately position the instrument at the telescope focus. Transport rails allow the instrument to be moved on its cart between the focal station and a storage location.

The entire instrument is contained in a windowed, purged enclosure to protect the optical components against dust and other contaminants. The electronics are mounted in an EMI tight, glycol cooled equipment rack that provides for service access to all of the electronics except for the CCD controllers, guide camera head and guider motion controller, which are mounted inside the instrument enclosure. The optical and mechanical configuration of KCWI is illustrated in block diagram form in Figure 6. The KCWI key performance parameters are listed in Table 1.

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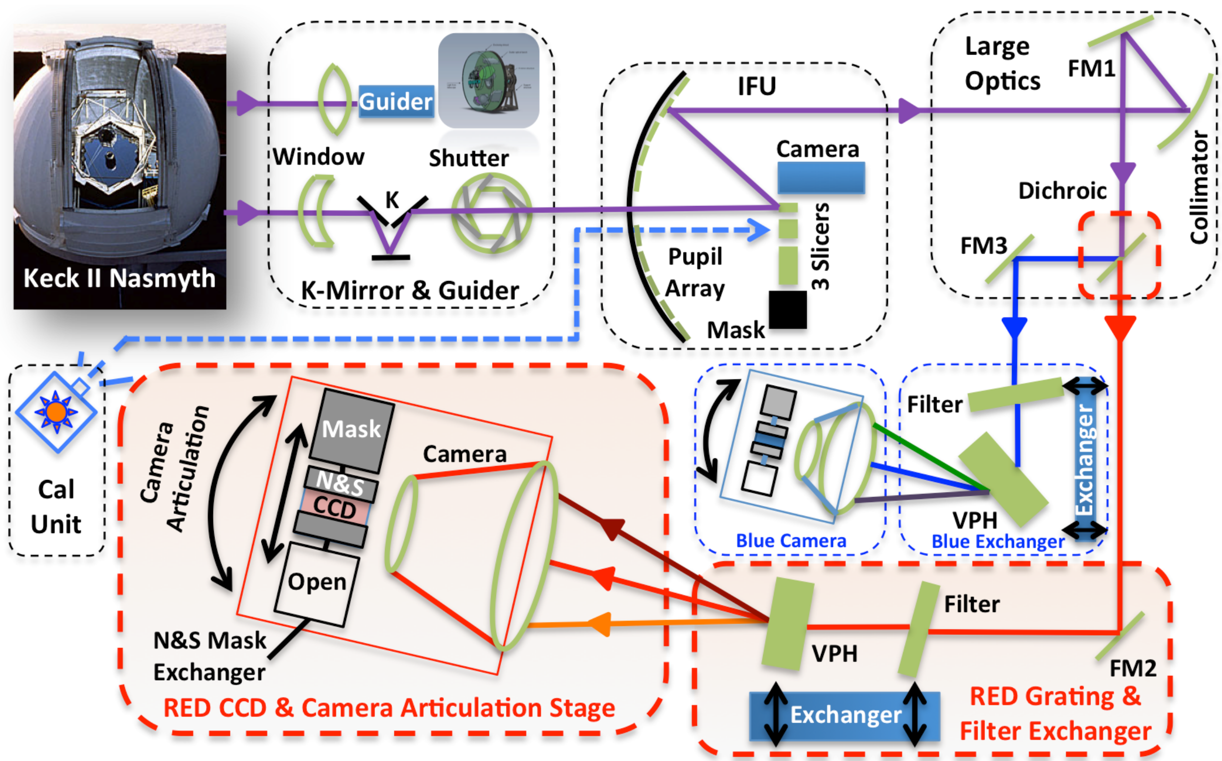

Figure 6: A block diagram of KCWI

Table 1: Key performance parameters of KCWI

Parameter	Value
Field of View	Selectable: 20" x (8.4" to 34")
Spatial Res./Sampling	Selectable: 0.35" x (0.35|0.7|1.4)"
Spectral Resolution	Selectable: 1,000 to 20,000
Bandpass (with blue and red channels)	350 to 1050 nm
Efficiency	> 40% (instrument)
Light Bucket Sensitivity	200 LU in 10 hours
Background Subtraction	0.01% of sky
Plate Scale	0.15" pixel^{-1}

Figure 7 shows an isometric view of the KCWI optical layout. The second fold mirror (designated FMD) will be replaced with a dichroic beam splitter when the red channel is added to the spectrograph. The instrument is configured with the blue channel underneath the bench. Large common optical elements are on the bench top, along with ample space reserved for the red channel. The optical path common to the red and blue channels starts with light arriving at the Keck II Nasmyth focal station. The science light passes through a window to a K-mirror image de-rotator and a standard Uniblitz shutter to a selectable image slicer stack located at the telescope focus. The slicer stack sits on a linear stage that selects among 3 slicer formats, a direct imaging alignment camera, or a black mask. A calibration system with a deployable periscope mechanism directs calibration light onto the image slicer.

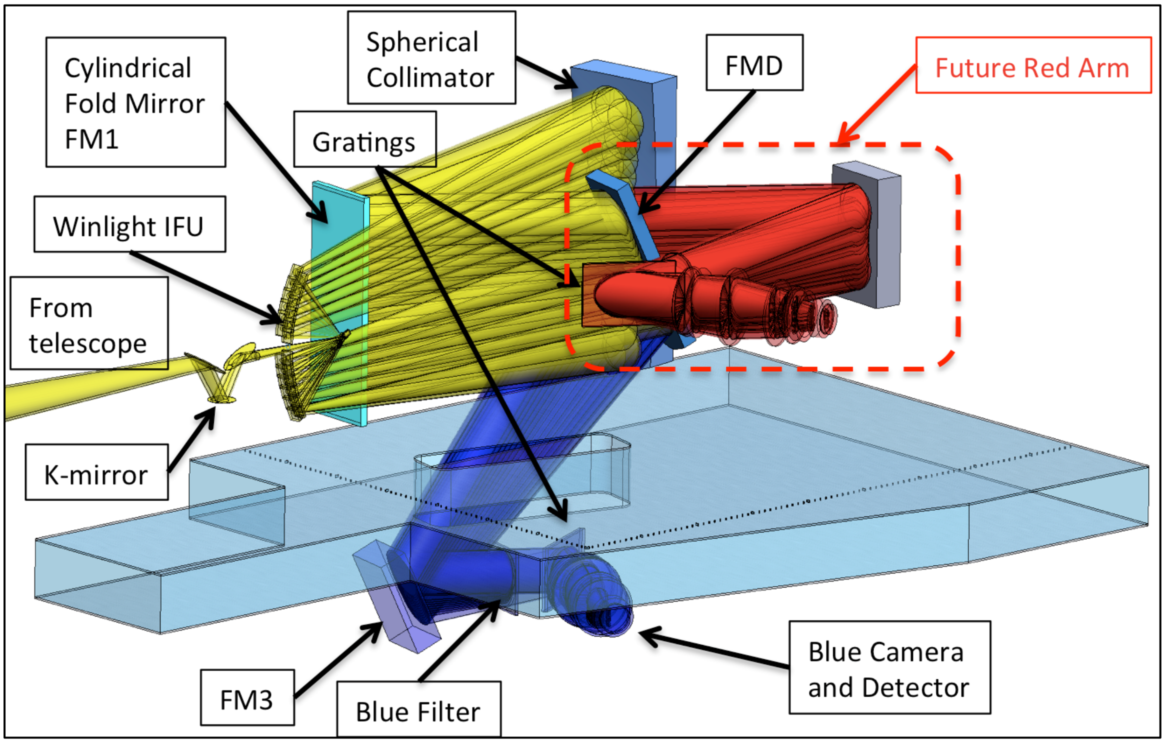

Figure 7: Isometric view of the KCWI optical layout

KCWI's novel integral field unit (IFU) will be fabricated by Winlight (France). The three selectable slicer mirror stacks provide 0.35", 0.7" or 1.4" spatial resolution (with commensurate 8.4", 16.8", or 33.6" FOV in one axis and a 20" FOV for all configurations on the other axis). These allow for a range of spectral resolutions from 1,000 to 20,000 depending on the grating. The image slicers are slightly curved to re-image the telescope pupil onto the VPH gratings used in each channel. Our configuration forms a Schmidt camera, with a virtual slit radius equal to the collimator focal length and the grating (stop) located at the collimator radius. The light from the pupil array proceeds to a spherical collimator and then to a wavefront-correcting cylindrical fold mirror (FM1), completing the portion of the optical path common to both the red and blue channels. A dichroic beamsplitter is used to divide the light between the two channels followed by a fold mirror to direct the light into the spectrograph. In the blue channel only version of the instrument a mirror is used instead of the dichroic beamsplitter. The dichroic will be added as part of the red channel.

Each spectrograph channel consists of a selectable bandpass filter, a selectable, variable tilt grating, and an articulated CCD camera. The blue channel fold mirror (FM3) and the remainder of the blue channel optical path are located below the KCWI optical bench. KCWI also incorporates a selectable nod-and-shuffle (N&S) mask, which covers 2/3 of the CCD active area when deployed to enable two patches of sky to be observed alternately (one patch of sky is hidden under the mask while the other is observed) during the course of a single integration for improved background subtraction with only a single detector readout.

KCWI is currently in the detailed design phase with a detailed design review of the blue channel only instrument planned for October 2012. First light at the telescope is planned for mid-2014.

3.5 Telescope Control System Upgrade

The telescope control system upgrade (TCSU) is an internally led project to develop a replacement for the hardware and software used to point the Keck telescopes and to track observational targets using guiding information provided by the MAGIQ guider software. Development of the upgrade began in 2010 and the project passed its preliminary design review in September 2011. The project is planning to hold a detailed design review in late September 2012.

The overall goals of the upgrade consist of improving performance, increasing reliability, reducing maintenance, and addressing serious obsolescence issues. This upgrade will use a distributed control solution in which subsystems are independent of each other simplifying maintenance and fault recovery. The telescope encoder systems will be replaced along with the existing custom logic boards and obsolete control computers. The control system software will move from VxWorks 5.x to Redhat Linux with the Messaging Realtime Grid (MRG) package. DeltaTau Ethernet connected bricks are being used for motion control and National Instruments MXI-RIOs are used for general purpose I/O. The system will continue to use EPICS to implement the control interface to other observatory systems and the custom pointing kernel will be updated to the more ubiquitous TCSPK.

The azimuth and elevation axis encoder systems will use the Heidenhain ERA 8400 linear optical encoder series with 40 μm line spacing for the incremental encoder scales and distance coded reference markers for absolute encoding. These scales are precision manufactured using photolithography. The azimuth and elevation encoders will employ an exposed scale with multiple read heads. The mechanical components of each encoder consist of four elements, (1) the Heidenhain tape scale, (2) multiple Heidenhain scanning read heads, (3) a mounting surface for the tape, and (4) hardware to position and protect the scanning read head above the tape scales. The electronics and software consists of a Heidenhain Encoder Interface Box (EIB 749) and the corresponding Linux and EPICS driver. The EPICS driver has been developed by WMKO using the EPICS ASYN Framework. Each EIB can handle up to four read heads. The EIB performs the incremental interpolation (4096 times) and all of the distance coded reference marker processing and provides the results over Ethernet.

New mounting tracks will be provided for both the azimuth and elevation encoder scales. These tracks will be fabricated as a number of manageable sized segments that will be bolted together on site to form the full mounting surface. Figure 8 shows a portion of the azimuth mounting track bolted to the outside of the existing azimuth journal. Also shown in the diagram is one of the azimuth read head assemblies. There are four read head assemblies spaced 90° apart. The read head mounting is part of a WMKO designed floating read head solution which not only addresses runout issues but also provides seismic protection. Figure 9 shows the complete elevation mounting track with all three read heads. Figure 10 shows the floating read head assembly design for the elevation axis and how it interfaces to the tape.

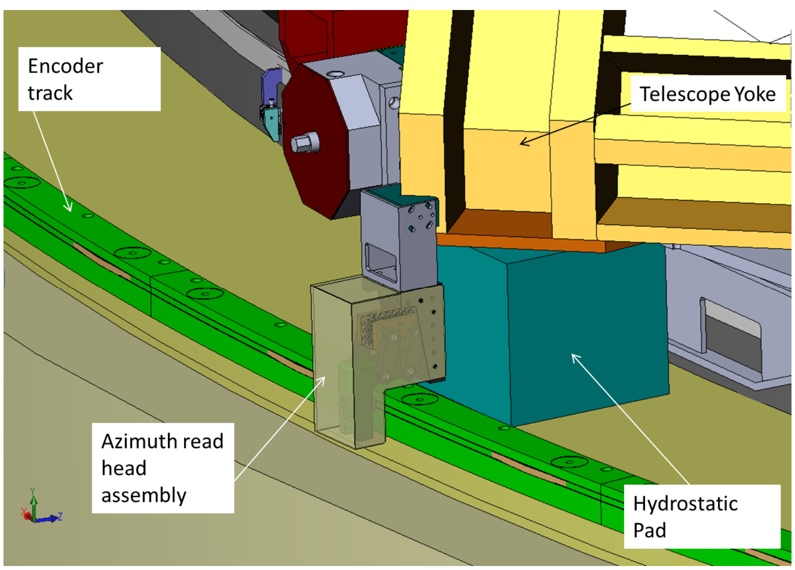

Figure 8: Portion of the azimuth encoder tape mounting track with one of the four read heads

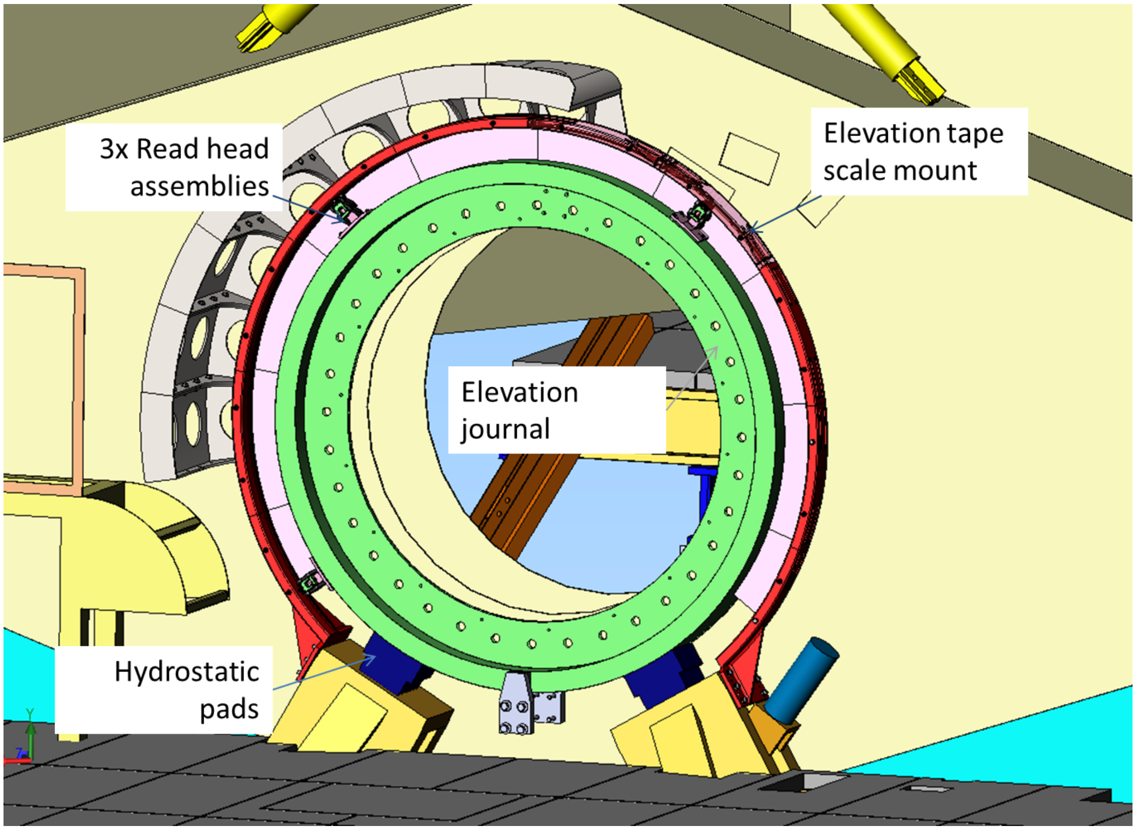

Figure 9: Elevation encoder track and read heads

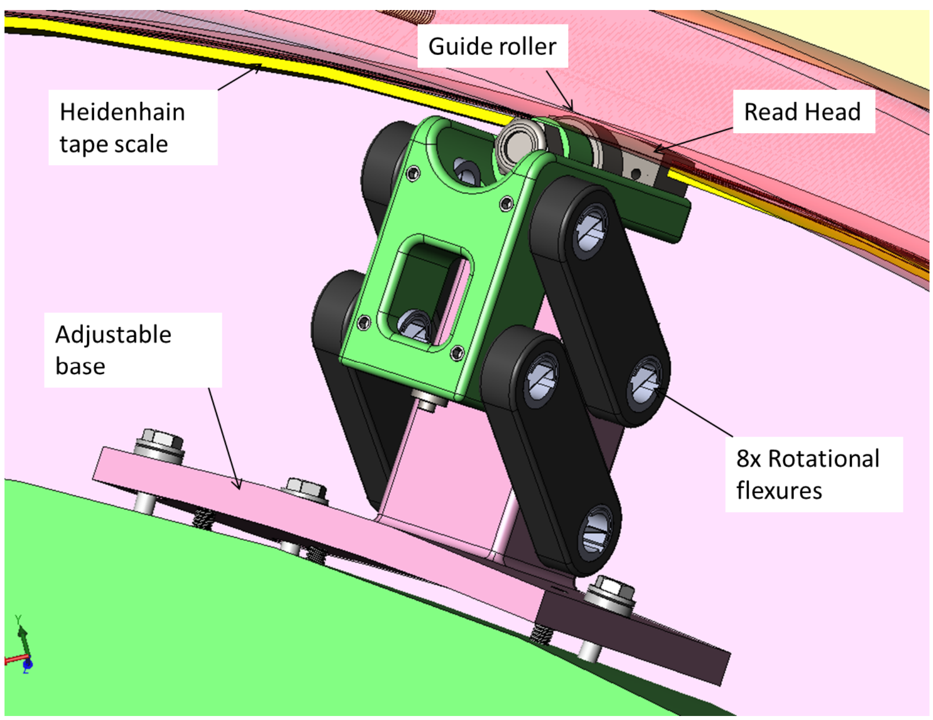

Figure 10: Read head assembly

During the detailed design phase the team has performed extensive prototyping. There is a dedicated lab at the Observatory headquarters which currently consists of computer servers with bc635PCIe, NI MXI and RocketPort Express PCIe cards, a full azimuth encoder prototype (including tape, four read heads, and Ethernet interfaces), a ControlLogix PLC and a representative set of FLEX I/O modules, a DeltaTau brick, and an NI MXI-RIO chassis with representative I/O cards. The lab is running Redhat Linux 6.2 with MRG; all drivers have been tested, as have all EPICS custom records and the core functionality of key subsystems. Work is currently ongoing to install a complete elevation encoder prototype on the Keck II telescope in July of this year.

The first installation of the complete upgrade is planned for early 2014 on the Keck II telescope. The upgrade will remain backwards compatible with older Observatory subsystems and allows for a phased migration to the new system.

3.6 Near-IR Tip/Tilt Sensing for the Keck I Adaptive Optics System

In July 2010 WMKO received a grant from the NSF's Advanced Technologies and Instrumentation program for the development of a near infrared (NIR) tip/tilt sensing (TTS) system for the Keck I AO system. The Keck I system was chosen since it has a higher power center launched laser and hence higher Strehl performance. The NIR TTS system will provide high bandwidth (up to 1 kHz) tip/tilt (TT) information from one to three stars in a ~120" diameter field to the existing Keck I LGS AO wavefront controller. The TTS system will be added to the existing LGS AO control system as shown schematically in Figure 11. A fold located just in front of the science camera reflects light to the NIR TTS assembly mounted on a focus stage. The TTS output is processed to provide TT control of the Tip-Tilt Mirror (TTM) as an alternative to the existing visible TTS (STRAP) or in combination.

Physically the NIR TTS system will be located at the edge of the existing Keck I AO bench just before the optical input of the Keck I science instrument, OSIRIS, as shown in Figure 12.

The NIR TTS optical system consists of dichroic beamsplitters to send the appropriate wavelength light to the TTS while transmitting the science light to OSIRIS, and relay optics to relay the required field to the TTS camera at the correct magnification. These optics include a field lens and fold mirror (outside the camera dewar), a dewar window, some reimaging optics, a pupil stop, and a filter. A motion control system with 3 degrees of freedom moves the dichroic exchanger between 4 positions, operates a focus stage for the relay optics and camera assembly, and moves a filter wheel between two filters and a blocked position. The camera uses a Hawaii-2RG detector in a dewar cooled by a closed cycle cryocooler. The detector is read out using an Astronomical Research Cameras detector controller with software modifications to the AO system wavefront controller to accept and process the NIR TTS data and real time telemetry modifications to allow storing and accessing the new real time data from the NIR TTS. AO operations software modifications are also required to support NIR TTS calibration and operation.

The detailed design review for the NIR TTS system was held in February 2012 and installation on the Keck I AO system is planned for early 2013.

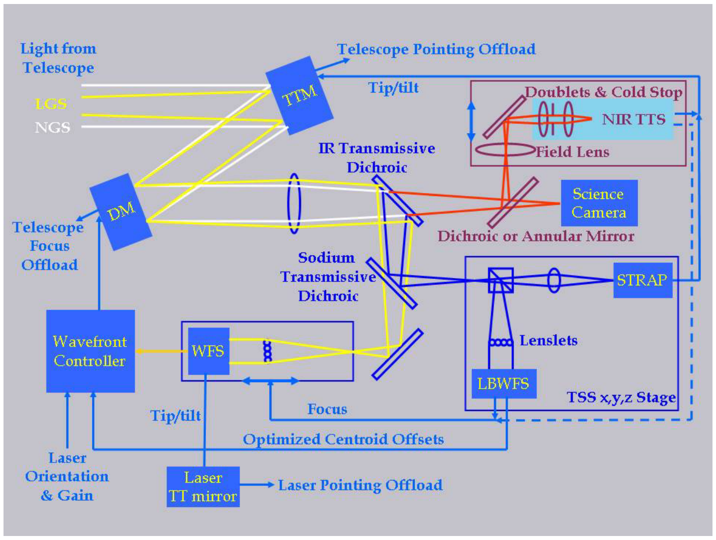

Figure 11: LGS AO control schematic with the new NIR TTS system added (upper right)

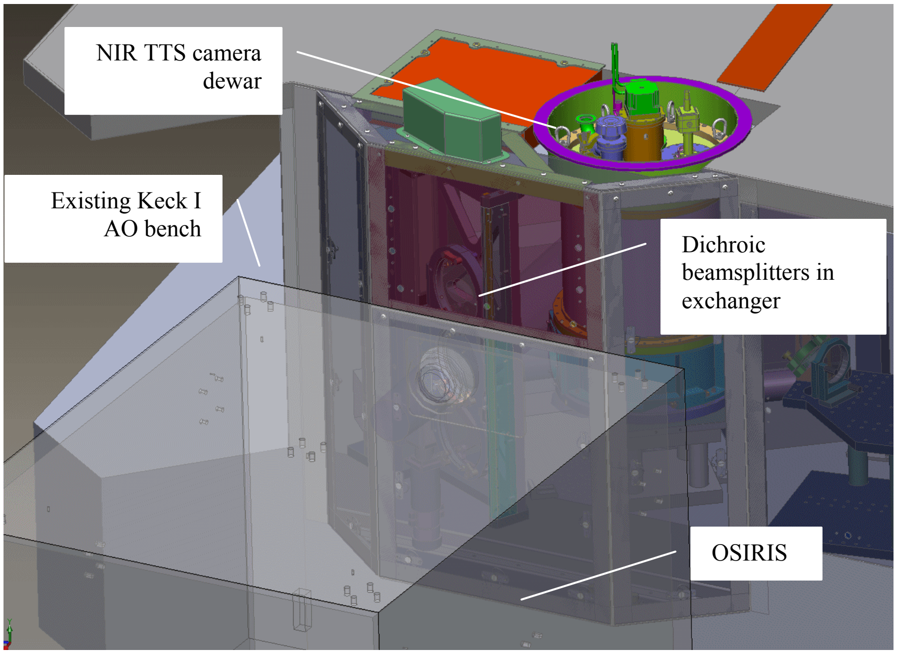

Figure 12: NIR TTS components on the Keck I AO bench

3.7 New Grating for OSIRIS

The OSIRIS integral field spectrograph[10] was commissioned at WMKO in 2005. When the instrument was commissioned we were aware that the sensitivity of OSIRIS was limited by the instrument's diffraction grating which had an efficiency in *J* band that is less than one-half of what was expected. At that time we were not able to obtain any interest from potential vendors in supplying a new grating due to the comparatively coarse ruling of 27.93 grooves per mm at a shallow blaze angle of 5.76°. In 2010 a new company, Bach Research expressed interest in making a new grating for OSIRIS. In collaboration with the UCLA IR Lab, and the Dunlop Institute at the University of Toronto, Bach Research is in the process of fabricating a new grating for OSIRIS[11]. A test ruling has demonstrated that the new grating should provide a significant performance gain with efficiencies of 60% or better in *J* band.

3.8 DEIMOS and NIRSPEC Upgrade Studies

We are currently studying the possibility of upgrades for the DEIMOS[12] and the NIRSPEC[13] instruments. The DEIMOS upgrade would replace the current CCD mosaic (eight 2k x 4k detectors) with eight thick substrate CCDs. The thick substrate will greatly reduce fringing at the red end of the spectrum as well as provide improved red QE. A broad band coating will provide excellent blue response to at least 400 nm. A nod and shuffle mode is also being considered, along with new gratings and filters to optimize the throughput and spectral coverage with the new CCD mosaic.

The NIRSPEC upgrade is investigating the prospects for improved radial velocity precision and more efficient high resolution spectroscopy ($R \geq 33,000$ to 60,000) by using a Hawaii-2RG detector in combination with a gas cell[14] to provide wavelength calibration fiducials with the observations.

4. CONCLUSIONS

Although the climate for funding new developments in astronomy continues to be challenging, the community of observers at WMKO continues to benefit from the strong collaborations between the Observatory and the instrumentation development teams at CIT, UCLA, UCO/Lick and UCSC. MOSFIRE represents a major new capability in near-infrared astronomy, while KCWI promises to be a leading capability in the visible wavelengths. Continued improvements in the AO systems of the Keck telescopes, and attention to the needs of the Observatory's critical infrastructure will ensure the continued scientific leadership of WMKO and its observing community.

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